Impacts of climate change and human activities on water resources in the Ebinur Lake Basin, Northwest China

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Abstract: Changing climatic conditions and extensive human activities have influenced the global water cycle. In recent years, significant changes in climate and land use have degraded the watershed ecosystem of the Ebinur Lake Basin in Xinjiang, Northwest China. In this paper, variations of runoff, temperature, precipitation, reference evapotranspiration, lake area, socio-economic water usage, groundwater level and water quality in the Ebinur Lake Basin from 1961 to 2015 were systematically analyzed by the Mann-Kendall test methods (M-K) mutation test, the cumulative levelling method, the climate-sensitive method and land-use change index. In addition, we evaluated the effects of human activities on land use change and water quality. The results reveal that there was a significant increase in temperature and precipitation from 1961 to 2015, despite a decrease in reference evapotranspiration. The Wenquan station was not significantly affected by human activities as it is situated at a higher altitude. Runoff at this station increased significantly with climate warming. In contrast, runoff at the Jinghe station was severely affected by numerous human activities. Runoff decreased without obvious fluctuations. The contributions of climate change to runoff variation at the Jinghe and Wenquan stations were 46.87% and 58.94%, respectively; and the contributions of human activities were 53.13% and 41.06%, respectively. Land-use patterns in the basin have changed significantly between 1990 and 2015: urban and rural constructed lands, saline-alkali land, bare land, cultivated land, and forest land have expanded, while areas under grassland, lake, ice/snow and river/channel have declined. Human activities have dramatically intensified land degradation and desertification. From 1961 to 2015, both the inflow into the Ebinur Lake and the area of the lake have declined year by year; groundwater levels have dropped significantly, and the water quality has deteriorated during the study period. In the oasis irrigation area below the runoff pass, human activities mainly influenced the utilization mode and quantity of water resources. Changes in the hydrology and quantity of water resources were driven primarily by the continuous expansion of cultivated land and oasis, as well as the growth of population and the construction of hydraulic engineering projects. After 2015, the effects of some ecological protection projects were observed. However, there was no obvious sign of ecological improvement in the basin, and some environmental problems continue to persist. On this basis, this study recommends that the expansion of oasis should be limited according to the carrying capacity of the local water bodies. Moreover, in order to ensure the ecological security of the basin, it is necessary to determine the optimal oasis area for sustainable

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development and improve the efficiency of water resources exploitation and utilization.

Keywords: climate change; human activities; runoff; water resources; groundwater level; climate-sensitive method; Ebinur Lake Basin

1 Introduction

Water resources strongly influence social and economic development in arid regions (Boehmer et al., 2000; Wang et al., 2017). Moreover, water systems are highly sensitive to climate change (Patz et al., 2000). According to the Fifth Assessment Report of the Intergovernmental Panel for Climate Change, the global mean air temperature rose by 0.850°C between 1880 and 2012 (Carraro et al., 2015). Moreover, over the past 60 years, the mean annual temperature in Northwest China has been rising at a rate of 0.039°C/a (2.78 times the global average), while the amount of precipitation has been increasing at a rate of 1.00 mm/a (1.39 times the Chinese average rate). This indicates that Northwest China is highly sensitive to global climate change (Ohmura and Wild, 2002; Mora et al., 2013). In the future, climate warming will aggravate water shortages in Northwest China, and thereby cause more apparent threats to the ecological security (Chen et al., 2010; Chen et al., 2012).

Economic restructuring through agriculture, large-scale reclamation of unusable land, population growth, urban development, and land-use changes are the most evident examples of human activities affecting the Earth's natural ecosystems (Yang et al., 2017, 2019, 2020; Gu et al., 2020). Land-use management for sustainable development is an important research field for both global and regional environmental change (Alvarenga et al., 2015; Priess et al., 2015; Madhusoodhanan et al., 2016). In 1995, the International Geosphere Biosphere Program and the International Human Dimensions Program on Global Environmental Change instituted the Land-Use and Land-Cover Change (LUCC) research program. The impacts of LUCC on hydrology and water resources attracted the attention of scholars in the fields of geography, ecology, biochemistry, and environgeology (Huang et al., 2014; Liu et al., 2016; Mirzaei et al., 2016). Land-use change in a drainage basin not only influences local surface runoff, but also affects evaporation, water quality, water volume, and groundwater levels. Moreover, it has far-reaching impacts on the hydrological cycle and the distribution of water resources (Narsimlu et al., 2013; Harrison et al., 2015; Hammouri et al., 2017). In recent years, extensive research has revealed that the impacts of LUCC on hydrological processes in a drainage basin varies based on different geographical features (Lee and Biggs, 2015). Therefore, empirical studies on representative regions are required to establish a generalized theoretical system to account for the impacts of LUCC on hydrological processes in a drainage basin (Tamene et al., 2014; Buysse et al., 2016; Tzabiras et al., 2016).

In the Ebinur Lake Basin of Northwest China, humans have intensively exploited land and water resources over the past six decades (Viola et al., 2014; Leng et al., 2015; Shrestha and Htut, 2016). A series of hydraulic engineering projects (e.g., the construction of barrages, reservoirs, and canal systems) have also been undertaken (Hu et al., 2002; Abuduwaili et al., 2007; Xia et al., 2011). In addition, there has been a significant increase in the land under cultivation as well as population; land-use patterns have also changed considerably (Mu et al., 2007). A combination of these factors has considerably influenced the hydrological cycle of the basin. Significant changes in runoff distribution, surface evaporation, soil water regime, vegetation coverage interception, water quality, and water volume have also been observed (Hu et al., 2002). Lake surface area has remarkably decreased, accompanied by a drop in the groundwater level, water quality deterioration, cut-off in the Kuytun River, reduced inflows, and severe degradation of the natural vegetation. The lake ecosystem in the Ebinur Lake Basin has undergone retrogressive evolution, thus triggering conspicuous ecological degradation (Yao et al., 2014). Furthermore, such changes

have had considerable negative impacts on industrial and agricultural production, transportation, and the physical and psychological health of residents. In addition, changes in the environment can pose threats to social and economic development activities and to regional ecological security on the northern slopes of Tianshan Mountains and even in Xinjiang of Northwest China (Hu et al., 2002; Abuduwaili et al., 2007; Xia et al., 2011). Therefore, by exploring land use and focusing on water resources utilization, the present study investigated the facilitation of efficient exploitation of local water resources and promotion of ecological restoration through sustainable land use in the Ebinur Lake Basin, particularly with regard to hydrology and water resources. In addition, the results of the present study can offer theoretical guidance and reference information on the improvement of inland river ecology and conservation of water resources in arid regions.

Many scholars have provided key recommendations for the sustainable development of the Ebinur Lake Basin based on the data collected from the basin (e.g., runoff measurements from gage stations, groundwater level quantity and quality, evaporation, socio-economic data and remote sensing data) (Li et al., 2007; Mu et al., 2007; Dong et al., 2009; Qiao et al., 2010; Liu et al., 2011; Bai et al., 2012; Meng et al., 2015). The present study is different from the previous studies as it established a hydrological process variation analysis method, based on climate change and human activity responses.

Thus, this study comprehensively evaluated the impacts of climate change and human activities on hydrology and water resources in the Ebinur Lake Basin during 1961–2015, containing an analysis of changes in surface runoff, water resources distribution, lake area and lake volume. Furthermore, the effects of land use, including water conservancy projects, on total utilization of water resources, groundwater levels and water quality in the Ebinur Lake Basin are also determined and analyzed.

2 Materials and methods

2.1 Study area

The Ebinur Lake Basin lies between 43°38′N and 45°52′N and between 79°53′E and 85°02′E (Fig. 1) in Xinjiang Uygur Autonomous Region, Northwest China. It includes Jinghe County, Bole City, Wenquan County and Ala Pass City in Bortala Mongolian Autonomous Prefecture of Xinjiang, covering an area of 2.7×10^4 km^2. Given the large-scale agricultural reclamation and water diversion projects that have been undertaken in the Kuytun River Basin since the 1950s, the surface runoff connection between the basin and the Ebinur Lake has been nearly severed; therefore, only a limited amount of water enters the Ebinur Lake during the flood season (Qiao et al., 2010; Liu et al., 2011). Moreover, the Jinghe River and Bohe River are the major rivers influencing the hydrology of the Ebinur Lake Basin. In this study, the Ebinur Lake Basin refers mainly to the Jinghe River Basin and Bohe River Basin.

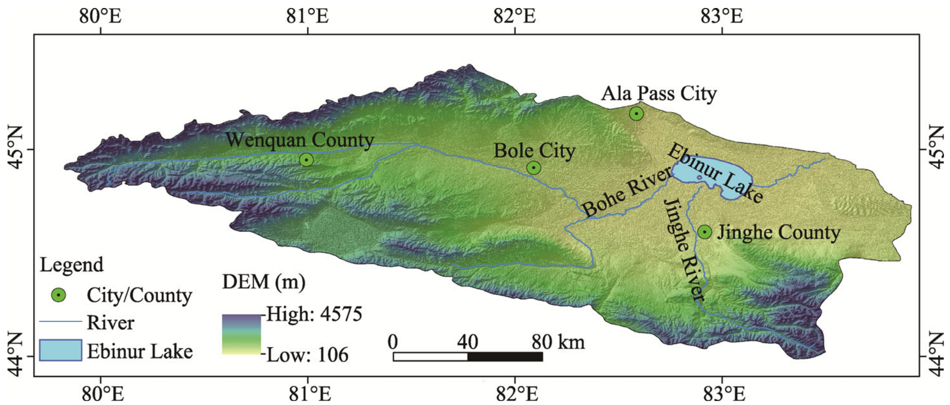

Fig. 1 Overview of the Ebinur Lake Basin. DEM, digital elevation model.

The Ebinur Lake Basin lies in the mid-latitude region of the Eurasian hinterland and is relatively distant from the ocean. There are high mountains to its north, west and south, resulting in a typical temperate arid continental climate characterized by low precipitation, high evaporation, abundant sunlight and extreme weather patterns. Such climatic characteristics, coupled with the unique landform, generate abundant and strong gusts of wind as well as frequent sand storms and dust movements in the basin.

In 2019, the total water resources of the Ebinur Lake Basin were 23.93×10^8 m^3, among which the water resources of Jinghe County, Bole City, Wenquan County and Ala Pass City were 10.15×10^8, 5.97×10^8, 7.76×10^8 and 0.05×10^8 m^3, respectively. There is an uneven distribution of precipitation throughout the year. Specifically, in the plain and mountainous areas, precipitation is mainly concentrated in spring and summer, accounting for 68.5%–85.0% of the annual precipitation, while it is less in winter, only accounting for 1.6%–12.1%. The maximum amount of four-month precipitation occurs between April and July in the plains and between May and August in the mountainous areas.

In the past, the Ebinur Lake Basin consisted of 47 rivers with various sizes. The plain area experiences low precipitation and produces virtually no runoff. Precipitation is the main source of river runoff in the mountainous area. However, most of the river runoff penetrates the soil and is lost at the alluvial fan outside the mountain pass. As a result, water enters the Ebinur Lake indirectly as an undercurrent or river supplement. Only a few rivers supply water directly to the Ebinur Lake during the flood season. Rivers with annual runoff exceeding 1.00×10^8 m^3/a include the Jinghe, Daheyanzi, Wuerdakesai and Bohe rivers (Bai et al., 2012; Meng et al., 2015). The Ebinur Lake Basin can be divided into two drainage basins on the basis of the associated river systems, that is, the Jinghe River Basin in the east, which mainly contains the Tuotuo, Aqiale and Jinghe rivers, and the Bohe River Basin in the west, which mainly incorporates the Daheyanzi, Wuerdakesai and Bohe rivers.

2.2 Data collection and management

Meteorological data were obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA; http://data.cma.cn). The data included monthly temperature, monthly precipitation and monthly evapotranspiration from ground-based meteorological stations covering a period from 1961 to 2015.

The hydrological data used in this study are as follows: (1) daily, monthly and annual runoff values of four hydrological stations (Jinghe, Bole, Wenquan, and Ala Pass) in the Ebinur Lake Basin from 1961 to 2015; (2) daily, monthly and annual runoff values of four inlets in the Ebinur Lake Basin from 1989 to 2019; (3) groundwater level, water quality and lake area of the Ebinur Lake Basin; and (4) irrigation data and water resources data from the Hydrographic and Water Resources Survey Bureau of Bortala Mongolia Autonomous Prefecture, Xinjiang Uygur Autonomous Region, China.

Land-use data for the study area were obtained from the NASA website (https://www.nasa.gov/) (Luo et al., 2003; Li et al., 2005). The data included mainly Landsat TM/ETM images for 1990, 2000, 2005, 2010, and 2015. To ensure the reliability of the data, we concentrated the five selected phases of remote sensing images in 8–9 months of the corresponding years, because more accurate vegetation interpretations can be obtained in the study area that had few clouds. Cloud pixels were removed using geometric rough corrections, radiometric calibrations, geometric fine corrections, and band-fusing. The Ecognition v 8.7 remote sensing classification software (Trimble Inc., Sunnyvale, CA, USA) was used to perform multi-scale segmentation and feature extraction of the generated remote sensing images. We performed a visual interpretation relative to high-resolution images from Google Earth, and corrected the interpretation results by a field investigation based on the interpretation and vectorization of five phases of remote sensing images. Eleven land-use types were studied: river/channel, reservoir/pond, lake, saline-alkali land, bare land, sandy land, cultivated land, forest land, grassland, urban and rural construction land, and land covered with ice/snow. The Kappa coefficient of the data was more than 0.89, and the accuracy was greater than 85%. This

indicated a high accuracy of the data, which met the research requirement.

The social and economic statistical data used in this study included population, land use, district information introduction, economic indicators, etc. These data were mainly from the statistical yearbooks of Natural Resources Bureau and Family Planning Committee of Bortala Mongolia Autonomous Prefecture for 1961–2015 (Resources Bureau and Family Planning Committee of Bortala Mongolia Autonomous Prefecture, 1961–2015).

2.3 Methods

In arid basins, the impacts of climate change (including temperature, precipitation, and evaporation) on water resources are significantly reflected in the upstream runoff. Human activities affect all aspects of water resources, particularly in the middle and downstream regions below the runoff pass. Thus, human activities alter the water resource characteristics and distribution characteristics. In the present study, the following methods were applied.

2.3.1 Cumulative levelling

Cumulative levelling was determined as the difference between each origin value and the mean value, that is, the anomaly value. Additionally, the sum of the anomaly values was the cumulative anomaly sequence:

$$LP_i = \sum_{i=1}^{n}\left(R_i - \overline{R}\right), \tag{1}$$

where, LP_i, R_i and $\overline{R}$ are the cumulative values of the anomaly, annual value and annual mean value, respectively.

2.3.2 Mann-Kendall (M-K) trend test

The M-K trend test is an effective method for testing trends and abrupt time-series changes (Kadioglu, 1997). This study used the M-K monotonic trend test (Ling et al., 2012), which is a non-parametric test, to analyze the change trends and possible transition points of runoff in the Ebinur Lake Basin.

2.3.3 Trend analysis of reference evapotranspiration (ET_0)

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \tag{2}$$

where, ET_0 is the annual reference evapotranspiration (mm) accumulated from daily ET_0; Δ is the slope of the vapor pressure curve (kPa/°C); R_n is the net radiation (MJ/(m^2•d)); G is the soil heat flux density (MJ/(m^2•d)); γ is the psychrometric constant (kPa/°C); T is the daily average temperature (°C); e_s is the vapor pressure of air at saturation (kPa); e_a is the actual vapor pressure (kPa); and u_2 is the wind speed at a height of 2 m (m/s).

2.3.4 Land-use change index

The dynamic degree (K) of land-use changes and land-use transfer matrix analysis (Wang and Bao, 1999; Liu et al., 2000) were mainly used in the present study, as follows:

$$K = \frac{\frac{U_b - U_a}{U_a}}{t} \times 100\%, \tag{3}$$

$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix}, \tag{4}$$

where, U_a and U_b are the land-use data of two different periods; t is the time; and P_{nn} is the land-use type.

2.3.5 Quantitative discrimination of runoff change attribution

In this study, the proposed climate-sensitive method (i.e., hydrologic sensitivity analysis method (HSAM); Dooge et al., 1999) was used to characterize the total change in runoff.

$$\Delta Q_{\text{total}} = \Delta Q_{\text{climate}} + \Delta Q_{\text{human}}, \tag{5}$$

where, ΔQ_{total} is the total annual runoff variation (mm); and ΔQ_{human} and $\Delta Q_{\text{climate}}$ represent the runoff variation caused by human activities and climate change (mm), respectively. The formula can also be:

$$\Delta Q_{\text{climate}} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET, \tag{6}$$

where, $\partial Q/\partial P$ is the contribution rate of precipitation change to runoff change; $\partial Q/\partial PET$ is the contribution rate of potential evaporation to runoff change; ΔPET is the change in annual potential evapotranspiration (mm); and ΔP is the change in annual precipitation (mm). The quantitative effects of potential evapotranspiration and precipitation on runoff change can be expressed as:

$$\frac{\partial Q}{\partial P} = \frac{1+2S+3\omega S}{\left(1+S+\omega S^2\right)^2}, \tag{7}$$

$$\frac{\partial Q}{\partial PET} = \frac{-\left(1+2\omega S\right)}{\left(1+S+\omega S^2\right)^2}, \tag{8}$$

where, S is the aridity index; and ω is a model parameter that is related to vegetation type, hydraulic properties of the soil, and topography (Yao and Chen, 2014).

Therefore, Equation 5 can be expressed as:

$$\Delta Q_{\text{total}} = \frac{1+2S+3\omega S}{\left(1+S+\omega S^2\right)^2}\Delta P + \frac{-\left(1+2\omega S\right)}{\left(1+S+\omega S^2\right)^2}\Delta PET + \Delta Q_{\text{human}}. \tag{9}$$

3 Results

3.1 Climate change in the Ebinur Lake Basin

3.1.1 Temperature and precipitation changes in the Ebinur Lake Basin

An analysis of the annual temperature of the main watershed hydrological stations and the Ala Pass meteorological station was conducted for the period from 1961 to 2015 (Fig. 2a). It indicated obvious differences in the annual average temperature change in the watershed. The annual average temperature of the Wenquan station was 4.0°C, the annual maximum average temperature was 5.3°C and the annual minimum average temperature was 2.4°C. The difference between the annual minimum and annual maximum temperatures was 2.9°C. The annual average temperature at the Bole station was 6.4°C, and the difference between the annual maximum and annual minimum temperatures was as high as 3.9°C. However, the annual average temperatures at the Ala Pass and Jinghe stations were similar, with the values of 8.9°C and 8.0°C, respectively; additionally, there was a large difference between the annual maximum and annual minimum temperatures at the two stations. Overall, the annual variation of temperature in the Ebinur Lake Basin during 1961–2015 was relatively high. The warming trends and ranges in the mountainous area were relatively low, while the trends in the oasis and plain were relatively high, indicating that human activities contributed more to regional climate warming.

The trends in precipitation change at the four stations (Fig. 2b) revealed that the average annual precipitation at the Wenquan station was the highest, reaching 234.1 mm. At the Wenquan station, the maximum and minimum annual precipitation was 394.3 and 77.8 mm, respectively. The difference between the maximum and minimum annual precipitation was 316.5 mm, which was much greater than the average annual precipitation. This shows that the range of change in

precipitation at the Wenquan station during 1961–2015 was high. At the Bole station, the average annual precipitation was 191.9 mm, and the difference between the maximum and minimum annual precipitation was also large (224.5 mm). Furthermore, the average annual precipitation at the Ala Pass station and Jinghe station was low, with the values of 113.3 and 104.6 mm, respectively. Although the differences between the maximum and minimum annual precipitation at the Ala Pass and Jinghe station were lower than those at the Wenquan and Bole stations, the range was large, indicating a considerable change in precipitation during the study period. Moreover, precipitation in the mountainous area showed the maximum increase.

The variation trend of precipitation at the four stations was as follows: Wenquan>Bole>Ala Pass>Jinghe, indicating that the distribution trend of precipitation was: mountain>oasis>desert. Specifically, the Wenquan station is located in a high-altitude mountain area, which receives the maximum amount of precipitation; the Bole station is located in the oasis area, receiving the second highest amount of precipitation; the Ala Pass and Jinghe stations are in the mountain-desert ecotone, both of them having similar amounts of precipitation.

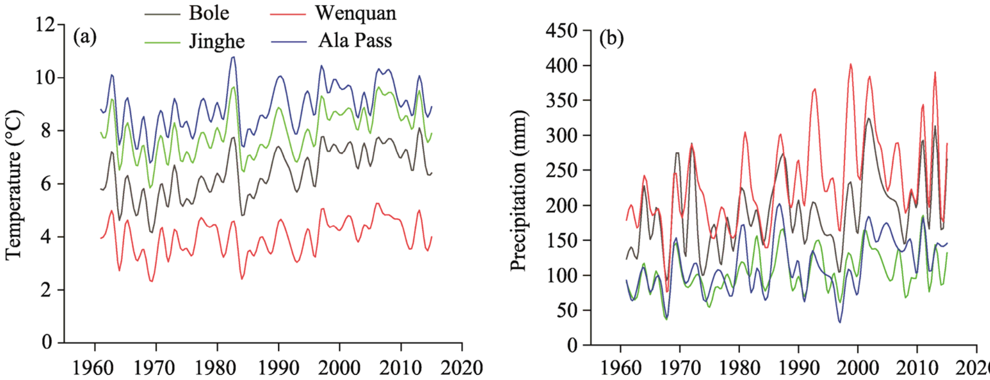

Fig. 2 Temperature (a) and precipitation (b) at the four hydrological stations in the Ebinur Lake Basin from 1961 to 2015

3.1.2 Evaporation change in the Ebinur Lake Basin

Based on the Penman-Menteith model, we estimated the change in the annual ET_0 in the basin from 1961 to 2015 and the result is shown in Figure 3. The analysis revealed that at the Ala Pass station, the average ET_0 was 1629.4 mm, the maximum value was 1873.3 mm, the minimum value was 1386.0 mm and the difference between the maximum and the minimum annual ET_0 values was 487.3 mm. The average annual ET_0 of the Jinghe station was 993.1 mm and that of the Wenquan station was 917.1 mm. The average annual ET_0 of the Wenquan and Jinghe stations also differed greatly, with the values of 316.6 and 407.5 mm, respectively. However, they were lower than that of the Ala Pass station. Overall, ET_0 exhibited a decreasing trend: desert>oasis>mountain. Given the high temperature throughout the year, ET_0 was high in the desert area, while low temperatures in the mountainous area greatly inhibited evaporation. ET_0 at the Ala Pass station experienced mutation in 1991. Specifically, before 1991, it was a positive anomaly and the fluctuation amplitude increased, but after 1991, the trend of decline was obvious. ET_0 at the Jinghe and Wenquan stations fluctuated significantly in 1993. Specifically, ET_0 showed an obvious decreasing trend before 1993 and then increased significantly after 1993. The fluctuation time of ET_0 was consistent with the change of ET_0 in Northwest China (Chen et al., 2014), and the fluctuation nodes were the same, but the ET_0 at the Ala Pass station showed a reverse fluctuation.

The variation trend of ET_0 at the three stations was as follows: Ala Pass>Jinghe>Wenquan. This shows that the distribution trend of ET_0 is desert>oasis>mountain, because ET_0 has a great relationship with the underlying surface. As the Ala Pass station is located in the desert area with high temperature and strong wind speed, its evaporation capacity is strongest, followed by the oasis area and mountainous area.

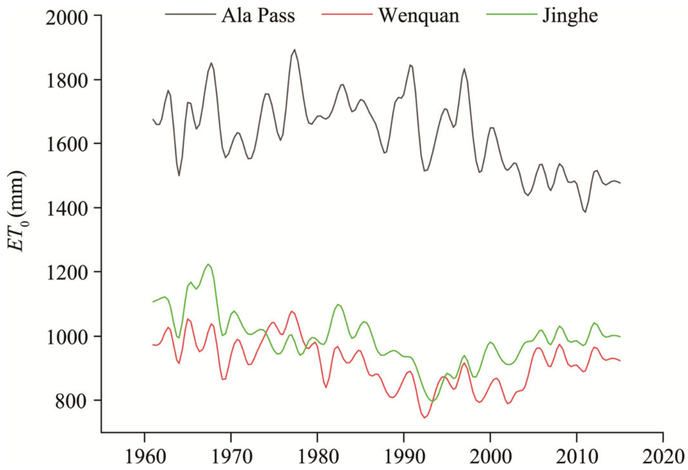

Fig. 3 Reference evapotranspiration (ET_0) at the three hydrological stations in the Ebinur Lake Basin from 1961 to 2015

3.2 Land-use change in the Ebinur Lake Basin

Based on Equations 3 and 4, we compared and analyzed the dynamic degree and transfer matrix of land use in the basin from 1990 to 2015. The results shown in Figure 4 demonstrated that from 1990 to 2015, urban and rural construction land, saline land, bare land, cultivated land and forest land exhibited an obvious expansion trend. Specifically, urban and rural construction land increased by 110.30 km^2, saline land increased by 112.94 km^2, bare land increased by 304.87 km^2, cultivated land increased by 1639.77 km^2 and forest land increased by 56.13 km^2. On the contrary, the areas under grassland, lake, ice/snow and river/channel decreased by 2117.13, 112.89, 9.27 and 10.69 km^2, respectively.

The spatial change trend of land-use pattern was that the areas of meadow, grassland and forest in the mountainous region greatly reduced due to large-scale reclamation. The increase in forest land was mainly associated with the conversion of cultivated land to forest land, while the decrease in forest land was mainly due to artificial felling of natural forests in the mountainous area and the degradation of desert forests in the lower reaches. Generally, the increase in forest land was greater than the decrease in forest land, the increase in cultivated land was mainly associated with the reclamation of desert land, and the increase in saline land was associated with the transformation of swamp grassland. The areas surrounding the reservoir were significantly affected by the development of fish ponds, aquaculture, rice cultivation and environmental degradation. Some of the reservoirs were converted to cultivated land and grassland, and the area was slightly reduced. Although the scale of agricultural production and the area of cultivated land increased, human activities also dramatically intensified land degradation and desertification. This is a major factor affecting the wetland ecosystem of the Ebinur Lake Basin.

3.3 Impacts of climate change and human activities on water resources in the Ebinur Lake Basin

3.3.1 Variation in surface runoff in the Ebinur Lake Basin

Inter-decadal changes in surface water resources (also known as flow) are closely related to the development and exploitation of water resources. They can directly affect water supply rate and water storage capacity. In addition, they are closely related to the sources and volumes of water supply. As the Jinghe station and Wenquan station are the outlet hydrologic stations of the Jinghe and Bohe rivers, respectively, they provided the most extensive coverage of the historical variation in hydrology. In the present study, the M-K mutation test and cumulative anomaly analysis were used to analyze the trends of annual runoff at the Jinghe station and Wenquan station between 1961 and 2015.

At the Jinghe station, the annual runoff data showed a decreasing trend from 1962 to 1976 (Fig.

5a and b). From 1977 to 1991, there was a fluctuating change in runoff, with an overall upward trend and an increase in the limited range. From 1992 to 2015, the range changed dramatically, with an obvious upward trend between 1992 and 2000; during 2001–2015, there was a downward trend. In 2015, the annual runoff further declined to its lowest point in the study period. During the period 1961–2015, the annual runoff showed no obvious sudden change, and the overall trend was gradual declining.

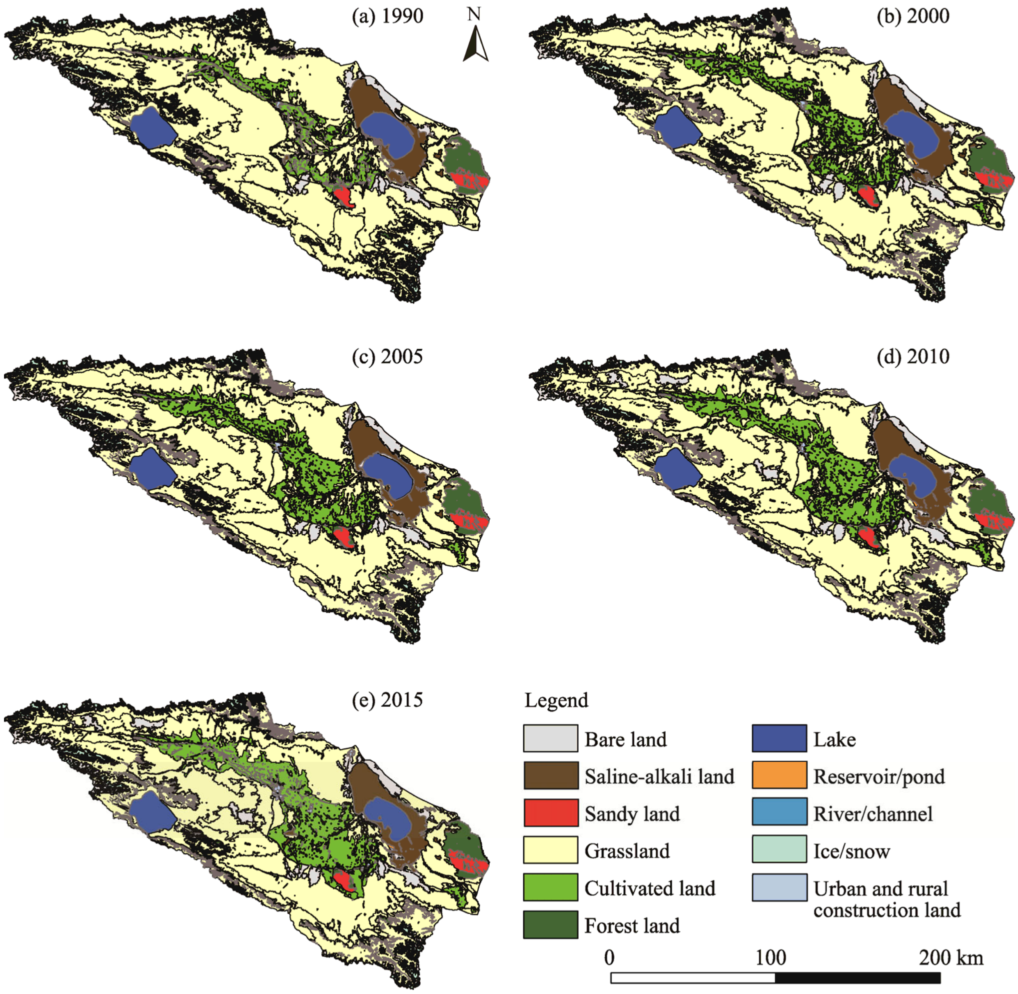

Fig. 4 Land-use change in the Ebinur Lake Basin from 1990 to 2015. (a), 1990; (b), 2000; (c), 2005; (d), 2010; (e), 2015.

The annual runoff at the Wenquan station fluctuated between 1961 and 1972, decreased from 1973 to 1983, and showed a marginal increase between 1984 and 1988 (Fig. 5c and d). Afterward, the annual runoff continued to decline from 1989 to 1996, exceeding a significance level of α=0.05. It should be noted that 1997 was a turning point. Based on the change in the accumulated anomaly runoff value at the Wenquan station, the annual runoff generally decreased before 1996 and increased after 1997. Overall, it exhibited a gradual increasing trend during the period 1961–2015. Therefore, 1997 was the critical point of the annual runoff at the Wenquan station.

Runoff at the Wenquan and Jinghe stations showed a downward trend from the 1960s to the 1980s, which may provide a plausible explanation for a large amount of water to be diverted from the river channel for the development of the basin. From 1990 to 2000, the annual runoff at the two stations exhibited an upward trend, but it was not consistent. However, this indicated that the recovery of runoff in the whole basin had a certain delay, which may have been affected by human

activities. Overall, runoff at the Wenquan station was high and changed remarkably in 1997, while runoff at the Jinghe station was small and did not change suddenly.

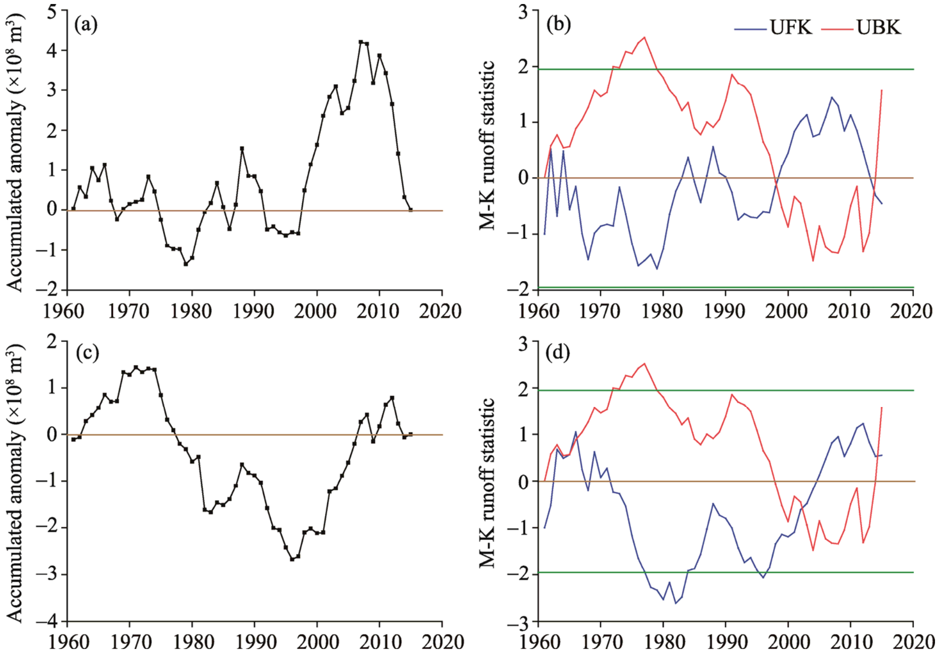

Fig. 5 Cumulative anomaly (a and c) and Mann-Kendall (M-K) mutation test analysis (b and d) of annual runoff at the Jinghe station (a and b) and Wenquan station (c and d) during 1961–2015. UFK represents a standard normal distribution. UBK= –UFK. The green lines represent a 95% confidence interval.

3.3.2 Quantitative discrimination of the impacts of climate change and human activities on runoff in the Ebinur Lake Basin

Based on Equations 5–8, we determined the impacts of climate change and human activities on runoff (Table 1). A comprehensive analysis showed that the contributions of climate change (precipitation increase and evaporation decrease) to the variation of runoff at the Jinghe and Wenquan stations were 46.87% and 58.94%, respectively; and the contributions of human activities to runoff variation were 53.13% and 41.06%, respectively. Runoff at the Jinghe station was severely affected by numerous human activities, such as the construction and mining of the Xiatianji Reservoir near the upper reaches of the Jinghe River. Although there was an overall increase in temperature and precipitation, runoff gradually decreased. However, at the Wenquan station, temperature and precipitation increased significantly, and the interference by human activities did not outstrip the impact of climate factors; thus, there was an overall increase in runoff.

Table 1 Impacts of climate change and human activities on runoff at the Jinghe and Wenquan stations

Station	ΔR (mm)	$\partial R/\partial P$	ΔP (mm)	$\partial R/\partial ET_0$	ΔPET (mm)	$\Delta Q_{climate}$ (mm)	Contribution (%)
Jinghe Pass	0.3	0.004	21.2	–0.002	–27.9	0.1406	46.87
Wenquan	5.4	0.044	66.5	–0.020	–40.0	3.0060	58.94

Note: ΔR, the change in annual runoff; ΔP, the change in annual precipitation; $\partial R/\partial P$, the sensitivity coefficient of precipitation to runoff change; $\partial R/\partial ET_0$, the sensitivity coefficient of potential evapotranspiration to runoff change; ΔPET, the change in annual potential evapotranspiration; $\Delta Q_{climate}$, the runoff variation caused by climate change.

3.3.3 Annual variation in lake area and inflow of the Ebinur Lake Basin

From 1950 to 2019, the area of the Ebinur Lake decreased significantly (Fig. 6) as a result of human activities. In 1950, the Ebinur Lake covered an area of 1200 km^2; a decade later, it declined to less than 900 km^2. In the 1970s, the area decreased to approximately 600 km^2.

Furthermore, from the early 1980s to the early 1990s, the lake maintained an area of approximately 500 km^2. From the late 1990s to 2005, the Ebinur Lake exhibited a recovery and expansion trend. Between 2002 and 2004, the Ebinur Lake expanded to an area greater than 800 km^2, but then it showed a continuous decline. In 2013, the lake declined to a minimum area of 408 km^2. After 2015, with the strengthening of ecological environment management, the lake area began to recover gradually. In 2016 and 2017, the lake area exceeded 520 km^2, and in 2018 and 2019, it increased to 630 km^2. Overall, from 1950 to 2019, the lake area decreased by 564 km^2, with an average annual decrease of 8.06 km^2.

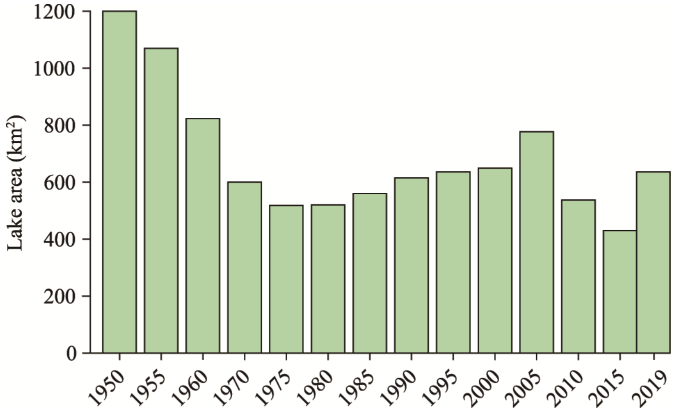

Fig. 6 Changes in the area of the Ebinur Lake from 1950 to 2019

Although natural factors such as high evaporation and less precipitation influence the area of the lake, intensive human activities, such as the construction of reservoirs and barrages in the upper reaches of the Ebinur Lake Basin and large-scale oasis development, have decreased the amount of water entering the Ebinur Lake annually. This is the major reason for the decline in the Ebinur Lake area and the degradation of its ecological environment.

Figure 7 demonstrated that in the past 31 years (1989–2019), the inflow into the Ebinur Lake had a fluctuating and decreasing trend. The water inflow into the lake was divided into five stages. Specifically, from 1989 to 1997, there was a decreasing trend in water inflow into the lake, with the value in 1997 (2.75×10^8 m^3) being the lowest. From 1998 to 2002, there was an increasing trend in water inflow into the lake, which reached its peak value in 2002 (12.23×10^8 m^3). Moreover, between 2003 and 2013, there was a continuous decreasing trend in water inflow into the lake, with the value in 2013 being merely 2.99×10^8 m^3. Correspondingly, the water storage capacity decreased from over 30.0×10^8 m^3 to only approximately 7.0×10^8 m^3. In 2002, the abnormal amount of water entering the lake was due to excess precipitation and high runoff discharge. However, the unique situation in 2002 did not mean that the amount of water that entered the lake over the years was high. In 2014–2016, with improvements in ecological status and conservation of water resources, the water inflow into the lake gradually increased. The amount of water entering the lake in 2016 reached the second peak (9.08×10^8 m^3) during the study period. From 2017 to 2019, the amount of water entering the lake remained above 5.00×10^8 m^3; furthermore, it continued to show a tendency to increase.

3.3.4 Variation of water use in the Ebinur Lake

From 1961 to 1965, the population in the basin increased from 7.79×10^4 to 13.78×10^4 (Fig. 8a). In the same period, the volume of water diversion reached a peak of 27.01×10^8 m^3. The main reason for the high rate of water diversion was the large-scale development in the river basin, including flood irrigation of crops. During this period, water use was unrestrained. During 1965–1985, the population continued to grow rapidly, and reservoirs and canal systems were constructed, so water diversion began to decrease. From 1985 to 1990, due to a large increase in population and the reclamation of land for cultivation, the amount of water diverted increased by 1.44×10^8 m^3. However, between 1990 and 2005, the rate of population growth declined

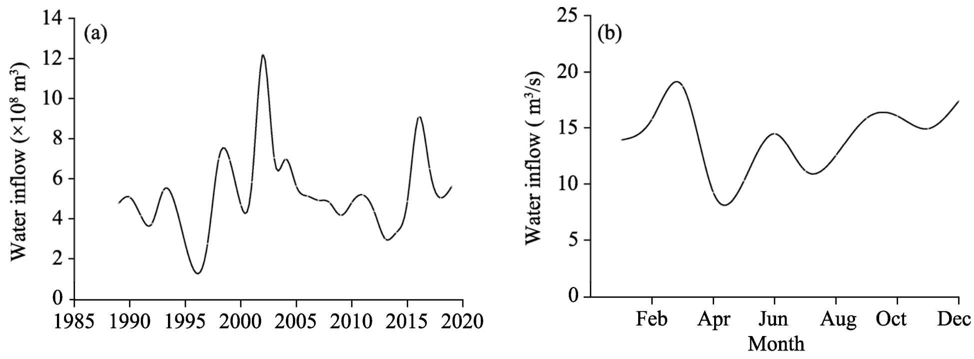

Fig. 7 Amount of water entering the lake (a) annually and (b) monthly during the period 1989–2019

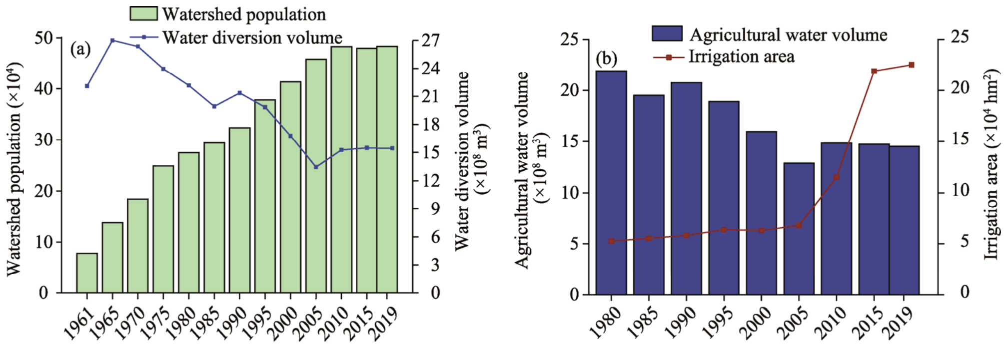

Fig. 8 Population and water diversion volume during 1961–2019 (a) and agricultural water use and irrigation area during 1980–2019 (b) in the Ebinur Lake Basin

considerably, and the basin conserved many water resources through the construction of impervious channels and the development of water conservation facilities, such as sprinklers and dropper systems. This resulted in a continuous reduction in the volume of the water diverted. From 2005 to 2019, the population increased gradually, leading to a simultaneous increase in the area of cultivated land, which led to a rise in the volume of water diverted; after 2010, the volume of water diversion was 15.20×10^8 m^3. Overall, between 1961 and 2019, the rapid increase in population and the expansion of oasis area exerted a great pressure on the development and utilization of water resources.

Changes in the agricultural water use can be divided into three stages (Fig. 8b). Specifically, during 1980–2005, agricultural water consumption declined because of the improvement in the anti-seepage ability of the canal system, the adjustment of crop structure and the gradual adoption of high-efficiency and water-conserving agriculture. Between 2005 and 2015, due to the continuous expansion of the oasis, land integration and development of high-tech farmlands, the area under irrigation increased rapidly to 15.00×10^4 hm^2. This was much more rapid than the increase in the area under water-conservation facilities (10.73×10^4 hm^2 in 2015). Therefore, the volume of water used in agriculture has marginally increased. After 2015, due to the implementation of the water resources management system, agricultural water consumption gradually decreased but remained above 14.50×10^8 m^3; moreover, the irrigation area increased steadily. For example, in 2019, agricultural water consumption was 14.52×10^8 m^3 and irrigation area was 22.52×10^4 hm^2.

According to the comprehensive analysis, the average proportion of agricultural water use in the Ebinur Lake Basin between 1980 and 2019 was greater than 94.00%, decreasing from 98.78% in 1980 to 94.12% in 2019. Agricultural water consumption accounted for the greatest proportion of the total water use in the basin.

3.3.5 Variation of groundwater in the Ebinur Lake Basin

From 2005 to 2019, the amount of surface water diversion showed a fluctuating decreasing trend,

while the surface water diversion and groundwater exploitation showed a fluctuating increasing trend (Fig. 9a). Water supply and groundwater exploitation reached their peaks in 2012. In addition, 2014 was the year of peak water use, with the total amount of water diversion and groundwater exploitation ranking second. These observations indicated that water consumption and the area under irrigation increased with an increase in socio-economic development. In cases where the surface water supply was inadequate, water consumption was increased by digging wells to extract groundwater. The large-scale extraction of groundwater partly cut off the spring water stream flows. This resulted in a significant reduction in the flow of plain springs. The amount of groundwater exploited annually in the basin was higher than 6.20×10^{8} m^3 in 2012–2016 and 2019. According to the report on ecological and environmental protection work of Water Conservancy Bureau of Bortala Mongolian Autonomous Prefecture since 2017 (Water Conservancy Bureau of Bortala Mongolian Autonomous Prefecture, 2019), the upper limit of the annual exploitation of groundwater was set at 3.54×10^{8} m^3, which translated to an overexploitation rate of over 170.00%.

During 1961–2019, numerous engineering projects have been launched to divert, store and transport water. Natural watercourses have been progressively replaced with more permanent artificial waterways. Consequently, there has been less seepage into groundwater from the watercourses in the Gobi-gravel zone, causing a continuous decline in groundwater levels. Data from long-term observation wells were used to analyze the annual changes in groundwater levels in the basin (Fig. 9b). From 1990 to 2019, groundwater levels at all three observation wells exhibited obvious decreasing trends. The greatest drop occurred in the Qingdeli Township. During the peak water use months, some wells did not produce water. Groundwater level reached its lowest value in 2016 (11.87 m) and 2017 (11.54 m). However, with the implementation of water and energy conservation, groundwater level gradually began to rise in 2018.

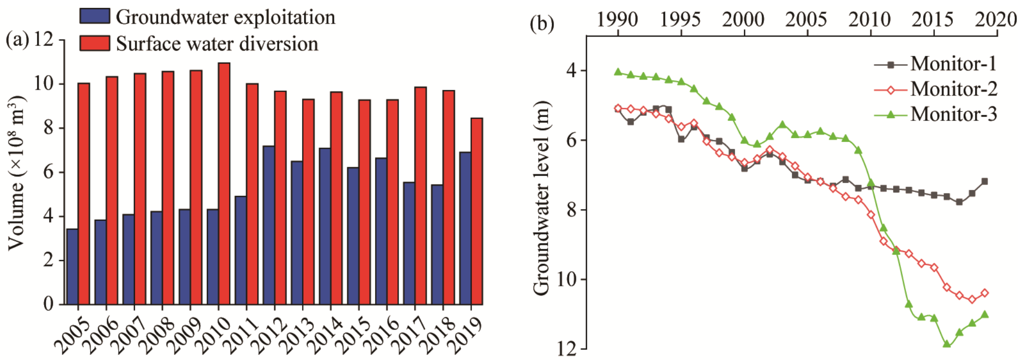

Fig. 9 Surface water diversion and groundwater exploitation during 2005–2019 (a) and groundwater level of three observation wells during 1990–2019 (b) in the Ebinur Lake Basin. Monitor-1, observation groundwater well was located at 200 m north of the Water Conservancy Bureau of Bortala Mongolian Autonomous Prefecture; Monitor-2, observation groundwater well was located in the state passenger transport company; Monitor-3, observation groundwater well was located in Qingdeli Township.

3.3.6 Variation of water quality in the Ebinur Lake Basin

From 1999 to 2019, the salinity values at the four hydrological stations (Wenquan, Jinghe, Bole and Ala Pass stations) exhibited an overall increasing trend (Fig. 10a). The added cumulative salinity values were 49, 115, 2 and 83 mg/L, respectively, during this period. The salinity values at the Wenquan and Jinghe stations respectively reached their peaks in 2015 and 2019 (175 and 262 mg/L, respectively). In 2014, the salinity values at the Bole and Ala Pass stations reached the maximum values of 403 and 415 mg/L, respectively. Given the construction of the Xiatianji reservoir, barrage and other water conservancy projects in the upper reaches of the Jinghe station in recent years, the salinity values were increasing. The salinity values of the other three hydrological stations showed a downward trend after 2015. Additionally, the declining trend in the salinity at the Bole station was the most significant, even reaching the level of 1999.

During 1999–2019, the water hardness values of the four hydrological stations showed an overall increasing trend (Fig. 10b). The water hardness increases at the Wenquan, Jinghe, Bole and Ala Pass stations were 16.3, 32.0, 5.0 and 18.0 mg/L, respectively. It should be noted that due to the lack of corresponding data at the Ala Pass station from 2016 to 2019, only the water hardness values of 1999–2015 were analyzed for this station. In 2019, the maximum water hardness values of the Jinghe and Wenquan stations were 94.8 and 135.0 mg/L, respectively. On the other hand, in 2014, the maximum water hardness values of the Bole and Ala Pass stations were 214.0 and 226.0 mg/L, respectively.

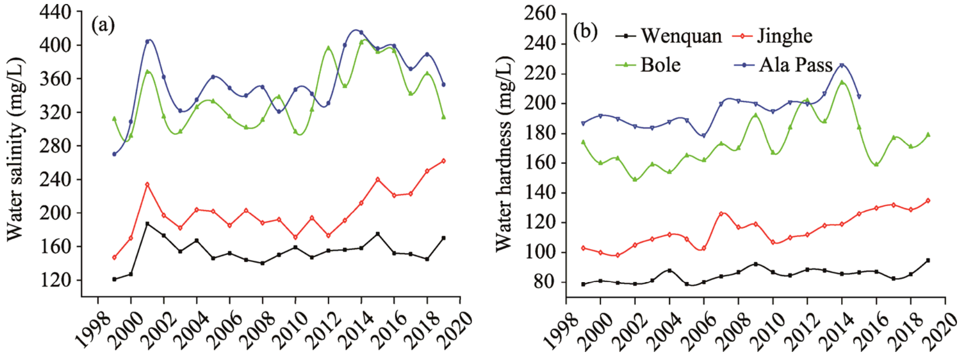

Fig. 10 Water salinity (a) and water hardness (b) at the four hydrological stations in the Ebinur Lake Basin during 1999–2019. It should be noted that due to the lack of corresponding data at the Ala Pass station from 2016 to 2019, only the water hardness values of 1999–2015 were analyzed for this station.

In general, the water salinity level of the Ebinur Lake exhibited an overall increasing trend from 2002 to 2018 (Fig. 11a). The degree of mineralization in 2014 was 2.54×10^5 mg/L higher than that in 2002. With respect to the tail lake, when the area of the lake increases, the water volume increases and the salinity level in the lake gets diluted. Conversely, the salinity level increases when the lake area shrinks. For example, from 2002 to 2009, the area of the Ebinur Lake shrank, and its salinity level increased correspondingly. However, the lake area increased from 2010 to 2011 while its water salinity level decreased. After 2012, the lake area began to decline again, and its salinity level increased until it reached the peak in 2014. After 2015, the salinity level decreased with an increase in the lake area.

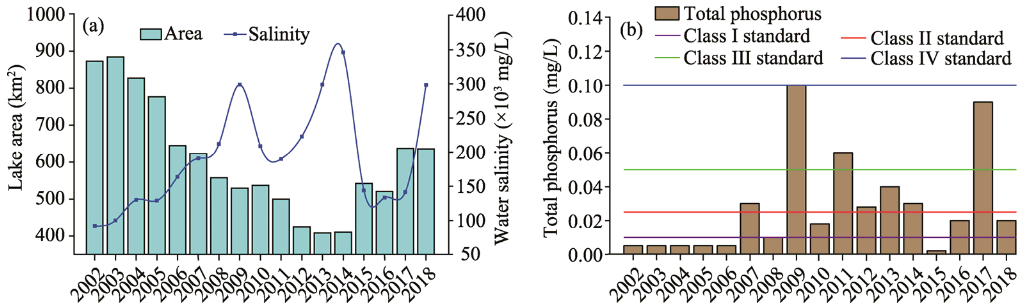

Fig. 11 Salinity and lake area (a) and phosphorus level (b) of the Ebinur Lake from 2002 to 2018. The standard classes of total phosphorus are referenced from the State Environmental Protection Administration and the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (2002).

From Figure 11b we can see that during 2002–2006, the phosphorus level of the Ebinur Lake belonged to the Class I (The State Environmental Protection Administration and the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2002), but it exceeded the Class II standard in 2007. In 2009, the phosphorus level reached 0.100 mg/L, which was categorized as Class IV and was considered eutrophic. From 2011 to 2014, the phosphorus level was associated with Class II and Class III standards. With the strengthening of environmental pollution control, the water quality of the lake has improved

significantly; for example, the phosphorus level of the lake was Class I in 2015. However, after 2016, the lake environment began to deteriorate. In 2017, the phosphorus level was close to the Class IV, and it was associated with Class I and Class II standards, respectively, in 2016 and 2018. Overall, from 2002 to 2018, the phosphorus level of the lake increased significantly, and the water tended to be eutrophic. The results showed that the water quality of the Ebinur Lake Basin deteriorated in recent years.

4 Discussion

Ebinur Lake Basin is a typical inland basin in Northwest China. Its water resources are sensitive to climate change and vulnerable to human activities (Patz et al., 2000). In the past 60 years, with the development of the oasis in the Ebinur Lake Basin, land use has changed dramatically, resulting in changes in the ecological environment. Further, with the warming and humidification of the climate in the arid area of Northwest China, the melting of glaciers and snow accelerated, and the uncertainty of water resources in the basin increased (Chen et al., 2010; Chen et al., 2012). The change of surface runoff is related to climate factors and human activities. When the river moves away the mountain sources, human activities have a great impact on runoff, especially through irrigation and increased farming activities to promote water consumption. Although the large-scale development of water resources has promoted the development of social economy (Viola et al., 2014; Leng et al., 2015; Shrestha and Htut, 2016), the scale expansion of oasis at the cost of water resources has also caused many ecological problems. If water resources are exploited unsustainably for a long time, the local ecosystem will be degraded and the social and economic activities will be affected. This study also confirms this point.

After 2015, a series of ecological protection projects have achieved remarkable results, mainly in the increase of water inflow into the Ebinur Lake, the recovery of the lake area and the rise of groundwater level. However, the exploitation of groundwater is still very large, the hardness and salinity of water at the hydrological stations are very high, and the water quality of the lake is still poor, indicating that the ecological changes have volatility and periodicity. The restoration and reconstruction of the ecological environment is a long-term process. In the future, it is important to continue to optimize the water use structure of the basin, strictly implement the water resources protection measures, identify the optimum area for sustainable development of oases, and improve the efficiency of water resources development and utilization (Water Conservancy Bureau of Bortala Mongolian Autonomous Prefecture, 2019).

Compared with previous studies, this study broadened the scope of key factors and was not limited to precipitation, runoff or groundwater. In addition, we focused on establishing a method to study the corresponding changes of human activities, natural climate change and water resources from a macro perspective. Then, the interaction of several key factors was analyzed by selecting climate, water resources, land use, water conservancy project, water consumption, groundwater level, water quality and social and economic development factors (Narsimlu et al., 2013; Harrison et al., 2015; Hammouri et al., 2017). Therefore, the variation of water resources caused by climate and land-use changes in the past 60 years were analyzed. The analysis method is a key innovation in this study, which makes this study different from the previous single factor research. We suggest that future studies should focus on the prudent planning of sustainable land-use patterns, the sustainable allocation of water resources in arid basins, the determination of the optimal scale of oasis development, the optimization of water system structure and the improvement of water resources utilization efficiency (Boehmer et al., 2000; Wang et al., 2017). These activities are essential for the sustainable management and development of water resources, the management of land-water interaction, the maintenance of the stability and security of fragile oasis ecosystems, and the promotion of the sustainable development of inland lakes and river basins.

5 Conclusions

This study revealed that climate change and land-use patterns in the Ebinur Lake Basin have been

significantly altered over the past six decades, with profound implications for the hydrology and water resources in the region. In this study, changes in runoff and hydrology of the Ebinur Lake Basin between 1961 and 2015 were analyzed using the cumulative levelling and Mann-Kendall test methods. The results showed that the annual runoff at the Jinghe hydrological station generally decreased, while the annual runoff at the Wenquan station increased, with fluctuations in 1997. The impacts of climate change (based on temperature, precipitation, evaporation, etc.) on water resources were reflected more prominently in the upstream of the basin. Therefore, the climate-sensitivity method was used to quantify the impacts of climate change and human activities on runoff. At the Jinghe and Wenquan stations, the contributions of climate change to runoff variation were 46.87% and 58.94%, respectively; and the contributions of human activities were 53.13% and 41.06%, respectively. That is, human activities influence all aspects of water resources, particularly in the middle and downstream areas below the runoff pass. Consequently, the changes and distribution characteristics of water resources are largely controlled by human activities. With the implementation of a series of ecological protection projects, the ecological environment of the Ebinur Lake Basin gradually began to recover after 2015. However, due to the continuous increase of water diversion in the irrigation area, the ecological water cannot be guaranteed, which is the fundamental reason for the continuous deterioration of the ecological environment and the unimproved lake improvement.

Acknowledgements

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